MULTIZONE MODELING AS AN INDOOR AIR QUALITY DESIGN TOOL

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ABSTRACT

Increased public awareness and changing industry standards have highlighted the importance of indoor air quality in the building design process. At the same time, many owners would like to construct buildings that conserve energy and minimize environmental impact. To accomplish both of these goals, the designer must be able to understand airflow rates, pressure relationships, and contaminant transport in buildings. This paper describes the use of a multizone model to perform design calculations for a new building on a college campus in the United States. The building incorporates a number of environmentally “progressive” features, such as natural ventilation, energy recovery, a biological wastewater treatment process, and CO_2 demand controlled ventilation. The multizone modeling tool CONTAM is used to size an exhaust fan for source isolation, select minimum ventilation quantities to control building related contaminants, and specify procedures for flushing out contaminants prior to occupancy. The multizone model is also used to predict transient contaminant levels, taking into account weather and associated infiltration. The generalization of these design and analysis techniques to a wider range of indoor air quality design applications is also discussed.

KEYWORDS: Air Quality, Design, Modeling, Source Control, VOC

INTRODUCTION

Ventilation is supplied to many non-residential buildings as part of the air handling system that provides space thermal conditioning. Requirements for thermal comfort and energy efficiency have traditionally received the lion's share of attention in the design of these systems. However, with increased public awareness and concern about indoor air quality issues, ventilation has begun to take a more central role in system design.

Space conditioning systems are sized by first identifying the worst case weather condition, or "design day" that the building is likely to experience. The thermal load is obtained by adding the contribution of the outdoor environment and other sources of heat such as people or equipment in the building. The system is then sized to satisfy the design day thermal loads and controlled to maintain thermal comfort during off-design conditions. Simulations of energy performance over a year of typical weather conditions might also be performed to predict peak demand and annual energy consumption.

In the past, many HVAC systems have been designed to provide outdoor air for ventilation either at a constant volume or in proportion to the thermal load. These strategies are limited in their ability to address outdoor pollutants, variations in indoor sources, and ventilation needs that may not coincide with thermal conditioning. However, systems can be designed to maintain acceptable indoor air quality using methods analogous to those used to achieve thermal comfort. Such a ventilation system could be sized to satisfy a "design day" contaminant load and controlled to maintain adequate ventilation while minimizing energy use throughout the year. This paper analyzes a case study building using the CONTAM multizone network airflow model to illustrate one form that this design process might take.

DEVELOPMENT OF THE BUILIDNG MODEL

A two-story classroom/office building located on a college campus in Ohio was used for the case study. Its design was intended to demonstrate innovative technologies and design techniques for reducing the environmental impacts of buildings. Some of its unique features include operable windows for natural ventilation, CO_2 demand controlled ventilation, HVAC system heat recovery, and an onsite biologically engineered wastewater treatment facility.

To begin the indoor air quality design analysis, a CONTAM model was developed, with the building rooms represented by discrete zones modeled as having uniform concentration. The rooms are connected to one another and the outdoors via paths that represent leakage sites such as doors and windows. The air handling system fans and ductwork are also specified. In this building, the system provides 100% outdoor air to all occupied spaces in quantities that satisfy ASHRAE Standard 62-99 [1], while ventilating "service" areas using local exhaust. The CONTAM model performs a mass balance calculation to estimate the flow between zones and the concentration of contaminants distributed by this flow [2].

Estimating building leakage was the most difficult aspect of model development. Door and window leakages were taken from published ASHRAE residential data [3]. Summarized results from 79 office and school buildings in the US, Canada and UK gives mean overall exterior envelope leakages in office buildings ranging from 0.7 to 2.4 cm^2 per m^2 of wall area, and in schools ranging from 0.6 to 1.9 cm^2/m^2 (all leakage areas given for a 10 Pa pressure difference and discharge coefficient of 0.6) [4]. Therefore, a distributed leakage of 0.75 cm^2/m^2 was specified for the exterior walls (a value at the low end of the range reported above) in addition to leakage at doors, windows, and other known sites as shown in Figure 1. Interior partitions, ceilings, and floors were modeled with twice the leakage of the exterior walls. This modeling strategy, while conservative, establishes a lower bound model that could be modified as additional leakage sites are revealed during and after construction without exceeding the range of "average" leakage areas for school and office buildings[4].

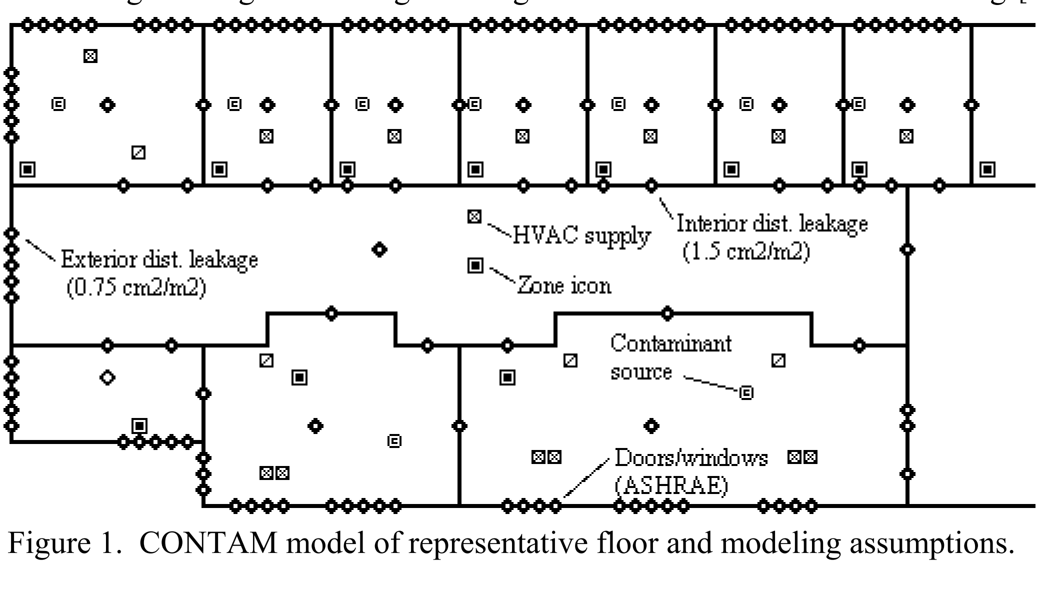

Figure 1. CONTAM model of representative floor and modeling assumptions.

Once developed, a few simple tests were applied to determine whether the model was realistic. A simulated fan pressurization test was performed to quantify the exterior envelope leakage by pressurizing the building with all interior partitions removed. The overall envelope leakage of the model was 1.1 cm^2/m^2 (at 10 Pa, C_D=0.6), which is slightly less than the average leakage documented in school and office buildings [4]. Additional pressurization tests to isolate door and window leakage showed that these account for roughly 35% of the total building leakage. This fraction has been reported to be about 15% in residences and 10-20% in commercial buildings [3,5]. Thus, this percentage may be slightly high, but is not unreasonably large considering the number of operable windows present.

SIZING A DEPRESSURIZATION FAN

Exhaust fans can be used to isolate pollutant sources, such as the attached biologically engineered wastewater treatment facility, from the remainder of the building. This facility is not expected to produce indoor air pollutants or odors at levels that might be harmful or irritating to building occupants. However, due to its nature and the possibility that odors might be generated in the case of malfunction, the capability to maintain a negative pressure relative to adjacent building spaces was desired.

The depressurization must be sufficient to achieve odor control, but low enough that door opening is not affected. Specific guidance was not available for this application, so a minimum recommendation of 12.4 Pa for smoke isolation in sprinklered applications was used in the design calculation [6]. An upper limit is also needed to prevent pressure forces from pulling the inward-opening doors open. The doors would be chosen so that the door closer force could be overcome easily by most people when the fan is off: in this case a 90 N door closer force was selected [6], indicating a maximum depressurization of 85 Pa. The multizone model was then used to select an exhaust fan to maintain depressurization between 12.4 Pa and 84.7 Pa.

Actual operating pressure differences in the constructed building vary depending on weather, operation of the HVAC system and local exhaust fans, and operation of doors and windows. The building leakage characteristics are also uncertain. Therefore, the exhaust fan should be selected to provide acceptable depressurization for a variety of operating situations over a range of exterior leakages. Eight operating conditions were investigated: demand-controlled ventilation fan operation (all on and all off), operation of restroom and local exhaust fans (all on and all off), and outdoor temperature (38°C and -23° C). These conditions were modeled for the expected building leakage, half that amount of leakage, and twice that amount of leakage.

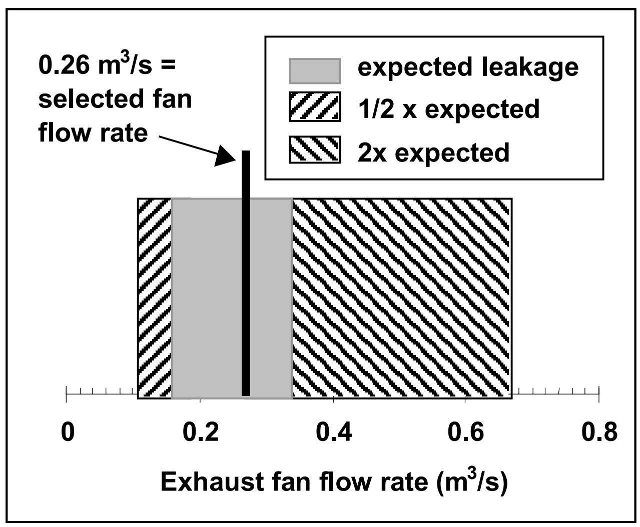

Figure 2. Exhaust fan flow rates for source isolation

Acceptable exhaust fan flow rates for the eight operating conditions are shown in Figure 2. For the expected building leakage distribution, the most stringent conditions required fan flows of at least 0.15 m^3/s and at most 0.33 m^3/s. For half the expected leakage, flows between 0.10 and 0.16 m^3/s would be appropriate, and flows between 0.26 and 0.67 m^3/s would be needed for twice the expected leakage. Since the three areas in Figure 2 do not overlap, one fan flow rate cannot satisfy all three leakage scenarios. Therefore, a designer might choose a fan flow rate of 0.26 m^3/s, which would be appropriate for up to twice the anticipated leakage. Using CONTAM to calculate the pressure rise, an appropriate fan could be selected. If the constructed building turned out to have less envelope leakage than expected, the fan speed could be adjusted.

DEMAND CONTROLLED VENTILATION STRATEGY

The building ventilation system can deliver 100% outdoor air in quantities that satisfy ASHRAE Standard 62-1999 [1]. A carbon dioxide demand controlled ventilation strategy is used in some intermittently occupied zones to adjust the ventilation rate based upon actual occupancy. A recent interpretation of Standard 62 requires that designers consider the possibility for buildup of non-occupant generated contaminants, particularly during unoccupied hours, and the lag time between occupancy changes and ventilation system response. The model was used to investigate these issues for a representative classroom.

The classroom has a design occupancy of 25, and requires 200 L/s of outdoor air to satisfy the 8 L/s per person requirement of Standard 62. The model was used to set minimum supply air volumes to control estimated building-related contaminant sources and specify appropriate time periods for purging after a night setback. Transient analysis can also be performed with varying operating schedules and weather conditions to demonstrate the off-design performance with respect to building and occupant-related contaminants.

Indoor air contaminants from building materials, furnishings, processes, and the outdoors may not be well controlled by a CO_2 demand controlled ventilation system since they may not be coincident with occupancy. The outdoor air was not of specific concern, and the wastewater treatment facility described earlier was the only unusual process present. Therefore, the primary group of non-occupant generated contaminants of concern were volatile organic compounds (VOCs) from building materials, furnishings, and activities.
VOC source strengths in buildings have been estimated from ventilation rates and contaminant concentrations. Average source strengths typically fall between 0.2 and 1.5 mg/m^2h [7,8]. One option for the designer is to consider this range of source strengths as well as the materials, occupants, and owner in analyzing the building. Modeling steady state conditions over a range of likely source strengths provides a range of ventilation rates likely to maintain acceptable contaminant levels. This much-simplified approach ignores both the time-dependent nature of the contaminant sources and adsorption/desorption effects, but allows the designer to estimate a minimum ventilation rate.

Steady state simulations were performed with the classroom receiving between 5 and 40% of its design ventilation rate, under the "design day" assumption of no wind or stack driven infiltration. Three levels of VOC emission were considered: low (0.2 mg/m^2), average (0.8 mg/m^2), and high (1.5 mg/m^2). Since the architect made an effort to choose building materials with low VOC emissions, actual source strengths in the building were expected to fall between 0.2 and 0.8 mg/m^2. The higher emission level was modeled to demonstrate the impact of design and operation for low VOC emission on minimum ventilation rates. Computed VOC concentrations are shown in Figure 3 for outdoor levels assumed zero.

The designer could use Figure 3 to select minimum settings for the demand controlled ventilation system to limit VOC levels during periods of low occupancy. While specific guidelines have not yet been developed, we know that average VOC concentrations of 1 mg/m^3 have been measured in residences, while concentrations in commercial buildings tend to be lower [8,9]. For example, if a designer chose to limit VOC concentration to 0.4 mg/m^3

above the outdoor level, Figure 3 specifies minimum setpoints of 20, 13, and less than 5% of the design ventilation rate for source strengths of 1.5, 0.8, and 0.2 mg/m^{2}h respectively.

Over longer unoccupied periods, such as nights and weekends, the ventilation systems in many buildings are shut down completely. The model can be used to specify a strategy for purging the building of contaminants following such a shutdown. If the ventilation system were shut down for a twelve-hour period each night, the classroom might experience a buildup of VOC, particularly if weather conditions were mild and infiltration limited. A "worst case" scenario would occur if the classroom ended the day with a VOC concentration of 0.4 mg/m^3, and very little infiltration occurred over the following twelve hours.

Average annual weather data for a nearby weather station were used to determine the infiltration design weather condition. Indoor-outdoor temperature difference and wind speeds were averaged for each twelve-hour overnight period, and sorted from lowest to highest. The "infiltration design day" was chosen as the lowest fifth percentile temperature difference and wind speed, applied from the prevailing wind direction. The model was then used to simulate the VOC concentrations with the classroom having an initial condition of 0.4 mg/m^3, and allowed to build up overnight with no mechanical ventilation and the infiltration conditions above. After twelve hours, the ventilation system was activated at 100% of its design ventilation rate. The resulting contaminant profile, shown in Figure 4, can be used to specify the time necessary for this purge process. If the designer would again like to limit the VOC concentration to 0.4 mg/m^3, purge times of 35, 25, and less than 10 minutes are required for source strengths of 1.5, 0.8, and 0.2 mg/m^{2}h respectively.

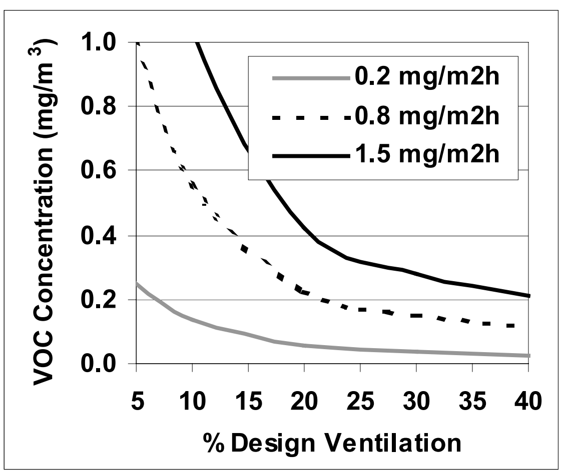

Figure 3. Minimum ventilation setpoint.

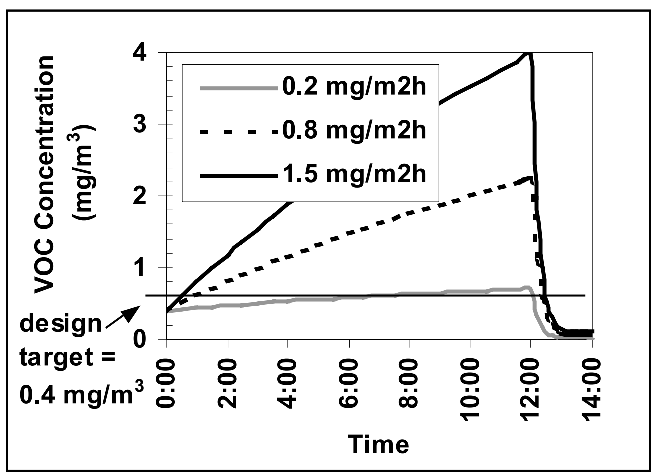

Figure 4. Specification of purge time.

DISCUSSION AND CONCLUSIONS

The case study building has been used to illustrate indoor air quality design calculations that make use of a multizone network airflow model and a procedure analogous to that which is commonly used to design systems for thermal conditioning. The system is sized to deliver ventilation air for the maximum number of occupants, and CO_2 demand control adjusts this volume based on the actual occupancy. The multizone model is used to calculate minimum ventilation rates to limit VOC concentration during periods of low occupancy and low infiltration. Transient simulations of an overnight period with very low infiltration (an infiltration "design day" condition) allows the designer to specify a pre-occupancy purge strategy for a case in which sorption effects are known to be unimportant.

This example illustrates the use of an available design tool and associated methods that could be applied to indoor air quality design. However, there are several weaknesses in terms of supporting data. A fairly comprehensive set of building leakage data are available for residential buildings, but commercial building leakage has not yet been summarized and made available in a convenient form. Some degree of experience is needed to idealize buildings for computational modeling, and it is often useful to perform calculations for a range of leakages. Features that make the assembly and adjustment of these models as fast and easy as possible are very helpful to the designer.

Perhaps most important is the need for more research and guidance to assist designers in estimating sources and setting limits on pollutants such as VOCs in contaminant-based design. Contaminant sink effects and variable source quantities, while not included in this analysis, are often very influential in real building situations. The multizone model has the capability to model these in more detail if the behavior of pollutants and materials is well understood in the design phase.

The case study results show differences in both the minimum ventilation quantity and purge times required to control VOC levels for the different source strengths modeled. This highlights the need for the designer to be able to estimate source strength as realistically as possible, as well as the benefit of designing and operating buildings with low-emitting materials and processes. For the system modeled in the case study, these differences apply to operational techniques rather than system size. Therefore, these techniques may also offer an opportunity to reduce costs and improve operating conditions in buildings where source strengths can be verified.

The design method introduced by this particular case study provides the means to size ventilation system components and specify operational strategies for critical "design-day" conditions to develop a preliminary design proposal. To further refine the design, annual simulations should be completed using the multizone model to estimate and minimize peak and annual energy demands, and to assess operation under predicted occupancy profiles.

REFERENCES

1. ASHRAE Standard 62-99. Amer. Society of Heating, Refrigerating, and Air Conditioning Engineers. Atlanta, GA.
2. Walton, G. 1997. *CONTAM96 User Manual.* NISTIR 6056. National Institute of Standards and Technology. Gaithersburg, MD.
3. ASHRAE 1997. *Handbook of Fundamentals*. American Society of Heating Ventilating, and Air Conditioning Engineers. Atlanta, GA.
4. Persily, A. 1999. "Myths About Building Envelopes." *ASHRAE Journal*. March 1999.
5. Persily, A. and Grot, R. 1986. "Pressurization Testing of Federal Buildings." STP 904. ASTM. Philadelphia, PA.
6. J. Klote and J. Milke. 1992. Design of Smoke Management Systems. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.
7. Levin, H. 1987. "The Evaluation of Building Materials and Furnishings for a New Office Building." IAQ 87 Practical Control of Indoor Air Problems 88-103. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA.
8. ASHRAE Standard 62R public review draft. 1996. Amer. Society of Heating, Refrigerating, and Air Conditioning Engineers. Atlanta, GA.
9. Brown, S., M. Sim, M. Abramson, and C. Gray. 1994. "Concentrations of Volatile Organic Compounds in Indoor Air - A Review." Indoor Air. p. 123-134.